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The Contribution of Population III to the Enrichment and Preheating of the Intracluster Medium

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ABSTRACT

Intracluster medium (ICM) abundances are higher than expected assuming enrichment by supernovae with progenitors belonging to the simple stellar population (SSP) observed in cluster galaxies, if stars formed with a standard initial mass function (IMF). Moreover, new results on ICM oxygen abundances imply that nucleosynthesis occurred with nonstandard yields. The hypothesis that hypernovae (HN) in general, and HN associated with Population III (Pop III) stars in particular, may significantly contribute to ICM enrichment is presented and evaluated. The observed abundance anomalies can be explained by a hypernovae-producing subpopulation of the SSP, but only if it accounts for half of all supernova explosions and if Type Ia supernova rates are very low. Also, the implied energy release may be excessive. However, an independent Pop III contribution – in the form of metal-free, very massive stars that evolve into hypernovae – can also account for all the observed abundances, while avoiding these drawbacks and accommodating a normal IMF in subsequent stellar generations. The required number of Pop III stars provides sufficient energy injection (at high redshift) to explain the ICM "entropy floor". Pop III hypernova pre-enrich the intergalactic medium, and can produce a significant fraction of the metals observed in the Lyα forest. Several testable predictions for ICM and IGM observations are made.

Subject headings:

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1. Introduction

Because rich clusters of galaxies are the largest virialized structures in the universe, their demographics are useful discriminants of fundamental cosmological parameters and theories of large scale structure formation. They also comprise an astrophysical laboratory for studying physical processes involved in galaxy formation and evolution: the depths of their dark matter potential wells imply that – unlike individual galaxies and perhaps even groups and poor clusters – they are good approximations to "closed boxes", and thus ideal sites for investigating the star formation history and chemical evolution imprinted in the properties of the accumulated baryonic matter component. The hot intracluster medium (ICM) is particularly suitable for such investigations due to the relatively straightforward measurement of its thermal and chemical properties via X-ray imaging spectroscopy. This is especially true now, following the launch of the new generation of X-ray Observatories that includes *Chandra* and *XMM-Newton*.

The ICM constitutes a vast reservoir of mass ($\sim 10^{14}$ $M_\odot$) and thermal energy ($\sim 3\ 10^{63}$ erg). Yet even though stars constitute only about a tenth of the baryonic mass, signatures of the influence of star formation on the ICM are apparent. Firstly, the ICM is enriched to a significant fraction of the solar metallicity (e.g., White 2000). The measured amount of metals *cannot* be explained as originating in a simple (coeval, homogeneous) stellar population (SSP) that also includes the stars observed today if the stellar initial mass function (IMF) was similar to that in the solar neighborhood and standard nucleosynthetic yields are assumed (Loewenstein & Mushotzky 1996, Section 2). Secondly, significant heating of the ICM is evident in departures in the (X-ray) luminosity-temperature, (total) mass-temperature, and (central ICM) entropy-temperature relations from predictions of self-similar (no-heating) scaling (e.g., Loewenstein 2000). Moreover, by some accounts, the required heating (> 1 keV/particle; Wu, Fabian, & Nulsen 2000) exceeds even that associated with the number of supernovae needed to enrich the ICM to its observed metal abundance, assuming a reasonable energy conversion efficiency. Metallicities and line widths of Lyα clouds demonstrate that the entire intergalactic medium (IGM) has been profoundly affected by physical processes associated with star formation (Cen & Ostriker 1999; Ellison et al. 2000; Aguirre et al. 2001; Cen & Bryan 2001).

Several, seemingly unrelated, recent astrophysical developments may shed some light on these puzzles, and motivate the present work. (1) Spectral analysis of *Newton-XMM* data is revealing relative O abundances well below predictions of standard enrichment theory (Tamura, et al. 2001; Kaastra, et al. 2001; Peterson, et al. 2001; Böhringer, et al. 2001). (2) Interestingly, calculations of nucleosynthesis in hypernovae (HN) – where explosion energies are 10–100 times greater than in standard supernovae – yield more extensive oxygen-burning

zones and hence depleted O abundances (Nakamura et al. 2001). (3) Furthermore, theoretical arguments now suggest (1) that the first, metal-free, generation of stars (Population III, hereafter Pop III) may be predominantly supermassive (Bromm, Coppi, & Larson 1999, 2001; Abel, Bryan, & Norman 2000, Larson 2001) (b) that such stars may be structurally stable over some mass range (Baraffe, Heger, & Woosley 2001), and (c) that these stars may end up exploding as HN with prodigious production of metals in substantially different relative proportions than in supernovae with Population I or II progenitors (Heger et al. 2001). In the following sections, I evaluate the feasibility and implications of a substantial contribution to the enrichment and heating of the ICM by HN in general and Pop III HN in particular. I adopt the following cosmological parameters: $\Omega_{\rm matter} = 0.3$, $\Lambda = 0.7$, and $H_{\rm o} = 70$ km s^{-1} Mpc^{-1}.

2. The Enrichment Paradox

The baryon fraction in a rich cluster of galaxies is $f_{\rm baryon} = 0.155(1 + \mu)$, where 0.155 is the measured gas fraction (Loewenstein 2000) and μ the mass ratio of stars (including remnants of evolved stars) to gas. Values of $f_{\rm baryon} = 0.16 - 0.20$ for $\mu \leq 0.3$ can be compared to $0.12 - 0.15$ obtained using Ω_{baryon} inferred from fitting big bang nucleosynthesis (BBN) models to measured high-redshift Ly-α absorber deuterium abundances (Burles, Nollett, & Turner 2001).[2] Consider chemical enrichment by an SSP, as is appropriate if dominated by early-type galaxies or their progenitors: most of the stellar mass in rich clusters resides in elliptical galaxies (Arnaud et al. 1992). For the broken power-law stellar initial mass function that characterizes a consensus of local IMF (hereafter, LIMF) estimates (Kroupa 2001), the number of Type II supernovae (SNII) explosions per mass of stars formed is $\approx 0.011\ {\rm M_\odot}^{-1}$, assuming all stars more massive than 8M$_\odot$ result in SNII. However for a coeval stellar population of age comparable to that of the universe, $\approx 40\%$ of the original mass will have been shed by stars more massive than the main sequence turnoff during the course of their evolution (adopting remnant masses from Ferreras & Silk 2000). Thus the number of SNII explosions per solar mass of *present-day* main-sequence stars plus remnants, the specific SNII rate $\eta_{\rm II} \approx 0.019\ {\rm M_\odot}^{-1}$ – a value insensitive to assumptions about the exact turnoff mass (0.87M$_\odot$), or upper (100M$_\odot$) and lower (0.1M$_\odot$) IMF cutoff masses. For IMFs

[2]The cluster data marginally favors higher values of $\Omega_{\rm matter}$, or higher Ω_{baryon} as inferred from recent cosmic microwave background anisotropy measurements (Hu et al. 2001). Lower values of Ω_{baryon} consistent with the higher deuterium abundance of one low-redshift Ly-α absorber and milder lithium depletion requires $\Omega_{\rm matter} < 0.13$ (Olive, Steigman, & Walker 2000) for consistency with the cluster data, assuming the latter is “representative”.

with single slopes of 1.3, 2.0 and, 0.7, $\eta_{\rm II} = 0.013$, 0.0084, and 0.067 $\rm M_\odot{}^{-1}$, respectively.

To illuminate the enrichment paradox, it is sufficient to consider the elements O, Si, and Fe. Adopted solar mass fractions, $f_\odot$, (Anders & Grevesse 1989) and yields for Type II and Type Ia (SNIa) supernovae ($\langle y_{\rm II}\rangle$ and $y_{\rm Ia}$, respectively; see Gibson, Loewenstein, & Mushotzky 1997) are displayed in Table 1.[3] I parameterize the contribution of SNIa explosions by the fraction of cluster baryonic (ICM-plus-stellar) Fe originating in SNIa, $f_{\rm Ia}$(Fe), that is estimated to be ~ 0.5 in the Galaxy (Timmes, Woosley, & Weaver 1996). The SNIa/SNII ratio, $0.135 f_{\rm Ia}({\rm Fe})/(1-f_{\rm Ia}({\rm Fe}))$, and O/Fe and Si/Fe abundance ratios as functions of $f_{\rm Ia}$(Fe) are displayed in Table 2 (see, also, Figure 1). Also shown (highlighted in Table 2) are the values of $\eta_{\rm II}$ needed to reproduce a typical rich cluster ICM Fe abundance of 0.4 solar, the Fe abundance corresponding to the canonical $\eta_{\rm II} = 0.019$ $\rm M_\odot{}^{-1}$, and the total supernova energy per unit gas mass, $kT_{\rm SN}$, for both these cases. Equal mass-averaged stellar and ICM abundances, 10^{51} erg per (Type II or Ia) supernova, and an ICM-to-stars mass ratio of 10 ($\mu = 0.1$) are assumed.

It is clear that one cannot simultaneously reproduce the observed 0.4 solar Fe abundance and Si/Fe ratio of ~ 1.7 (Fukazawa et al. 1999) if the ICM-enriching SNII and current stellar population derive from a single star formation epoch with the LIMF (see, also, Loewenstein & Mushotzky 1996). Given the observed Fe abundance, the Si abundance falls short by $\sim 50\%$ (see the $f_{\rm Ia}({\rm Fe}) = 0.66$ Table 2 entry and Figure 1) unless the number of SNII is increased by a factor ≈ 1.8 ($f_{\rm Ia}({\rm Fe}) = 0.38$ entry) – which also increases the supernovae heating by $\sim 60\%$. An increase in the average SNII Si yield from 0.14 to 0.24 $\rm M_\odot$ is required to reconcile the observed abundances with the LIMF – an increase not supported by any published SNII nucleosynthesis calculations.

Current understanding of star formation is sufficiently incomplete that the top-heavy or bimodal IMF inferred for the earliest generations of stars in cluster galaxies (or protogalaxies) by the ICM observations (see, also, Elbaz, Arnaud, & Vangioni-Flam 1995; Matteucci & Gibson 1995) cannot be ruled out *a priori* – and may even be supported by other lines of evidence (e.g., Mathews 1989). However, these scenarios are in conflict with the first precise X-ray measurements of O abundances by the detectors on the *Newton-XMM* Observatory (Tamura, et al. 2001; Kaastra, et al. 2001; Peterson, et al. 2001; Böhringer, et al. 2001). The O/Fe ratio in the best-fit spectral models for the galaxy clusters Abell 1795, Abell 1835, Sérsic 159-03, and Virgo ranges from $\sim 0.3-1.0$ solar, with the lowest values found in the cores of the latter two systems. If the ICM in these systems – all of which are cooling

[3]SNII yields are averaged over the IMF assuming a slope ~ 1.3 for massive stars; their variation with IMF slope is a second order effect when compared to differences in $\eta_{\rm II}$.

flow clusters – is intrinsically chemically inhomogeneous, both elemental abundance and abundance ratio estimates based on relatively simple models may not accurately reflect the true level and pattern of enrichment (Fabian et al. 2001). However, for the purposes of this paper I provisionally adopt these values. Combined with *ASCA* measurements of supersolar Si/Fe ratios (Fukazawa et al. 1999), confirmed with *Newton-XMM* for Virgo (Böhringer, et al. 2001), these indicate a relative underabundance of O compared to Fe and Si. The predicted O/Fe ratio is minimized for high values of $f_{\rm Ia}$(Fe); however, these produce unacceptably low Si/Fe ratios (Table 2). For example, $f_{\rm Ia}(\rm Fe) = 0.85$ implies O/Fe ~ 0.5, but Si/Fe ~ 0.7 (and also $\eta_{\rm II}$ less than half the LIMF value). Subsolar values of O/Fe imply Si/Fe < 1.3 solar.

It is possible that "standard" SNII O yields (Table 1) may be overestimated due to inaccurate reaction rates, an incorrect treatment of convection, and/or pre-explosion mass loss (Gibson et al. 1997). The O/Si abundance ratio can be lowered to ~ 0.5 by reducing the assumed IMF-averaged O yield by $\sim 40\%$; although, the observed Si/Fe ratio still requires an $\sim 80\%$ enhancement in the SNII rate per stellar mass. Here I consider a more radical alternative – significant enrichment by hypernovae. My aim is to determine whether the addition of a HN contribution might account for these preliminary indications of O/Si ~ 0.5 whilst maintaining consistency with the observed Si/Fe ratio (for some value of $f_{\rm Ia}$(Fe)); and, if so, to explore the resulting implications.

3. Hypernovae, Population III, and the ICM

3.1. A Hypernova-Progenitor Subpopulation

I initially investigate the case of a unimodal IMF where a fraction $f_{\rm HN}$ of the early-epoch massive stellar population – perhaps corresponding to the most metal-poor supernova progenitors – result in HN explosions rather than conventional SNII. The closed-box approximation is used: all nucleosynthetic products from both SNII and HN are assumed to be retained in the deep cluster potential well. Nucleosynthetic yields corresponding to the most extreme explosion kinetic energy studied by Nakamura et al. (2001), 10^{53} erg, are considered. Extended burning out to lower density regions results in relative depletion of O, but enhancement of Si and Fe. For the most massive He core model they consider, the ratios of yields in the 10^{53} erg model compared to those for 10^{51} erg are displayed in Table 1 ($\epsilon_{\rm HN}$). I adopt these as scaling factors in estimating the possible contribution of such HN to ICM metal enrichment.

Table 2 includes two entries for $f_{\rm HN} = 0.5$ that is required to produce O/Si ≈ 0.5.

The second, with $f_{\rm Ia}({\rm Fe}) = 0.23$, is tuned to produce a 0.4 solar Fe abundance assuming the canonical $\eta_{\rm II} = 0.019\ {\rm M}_\odot{}^{-1}$ and yields a Si/Fe ratio about 30% lower than typically observed in rich clusters (Figure 1). The first, with $f_{\rm Ia}({\rm Fe}) = 0$, simultaneously produces the correct O, Si, and Fe abundances with a modest increase of $\eta_{\rm II}$ to $0.025\ {\rm M}_\odot{}^{-1}$. The resulting heating is prodigious – ~ 25 keV/particle, equivalent to $\sim 3\ 10^{45}\tau_9^{-1}$ erg s^{-1} per L_* galaxy, compared to $\sim 10^{44}\tau_9^{-1}$ erg s^{-1} per L_* galaxy for $f_{\rm HN} = 0$, where the energy is released over an interval of $10^9\tau_9$ yr. The HN may have more modest energies $\sim 10^{52}$ erg; but, in that case the yield scaling factors will be closer to unity and the required value of $f_{\rm HN}$ correspondingly higher.

3.2. Hypernovae Associated with Population III

In addition to a parallel subpopulation, I consider a distinct star formation mode consisting of very massive ($> 100\ {\rm M}_\odot$) metal-free Pop III stars that ultimately produce ICM-enriching HN. I do not address, in detail, the issue of when and how completely the products of the two star formation modes are ejected from proto-galaxies; the dispersal of HN products may very well take place in pre-galactic fragments and the SNII products via subsequent galactic winds. I also characterize these HN with $f_{\rm HN}$ – the fraction of all SNII or HN progenitors that result in hypernovae. The absence of metals assures structural stability up until the onset of a pair-creation instability that proceeds the HN explosion (Baraffe et al. 2000). He core masses $M_{\rm core} = 100$ and $120\ {\rm M}_\odot$ (from progenitors of mass $\sim 200 - 250\ {\rm M}_\odot$), with corresponding explosion energies 4 and 7 10^{52} erg, and yield enhancement factors displayed in Table 1 (as $\epsilon_{\rm HN3}(100)$ and $\epsilon_{\rm HN3}(120)$, respectively) are utilized (adopted from Heger et al. 2000). The resulting enrichment and preheating are shown on the final two lines of Table 2, the former illustrated in Figure 1.

Intriguingly, unlike all other scenarios described above, the observed Fe, Si, and O abundances are simultaneously reproduced for a SNII per stellar mass ratio consistent with the LIMF (Figure 1), if $f_{\rm HN} = 0.005$ and $f_{\rm Ia}({\rm Fe}) = 0.59$ ($M_{\rm core} = 100\ {\rm M}_\odot$), or 0.20 ($M_{\rm core} = 120{\rm M}_\odot$). Of the 0.56 (0.58) keV per ICM particle produced by SNII+HN for $M_{\rm core} = 100$ (120), 0.08 (0.14) keV per particle originates in the HN component. This relatively modest energy, however, is released at very high redshift ($z \gtrsim 10$) where it has maximal effect on the entropy – and hence subsequent evolution and final state – of the proto-ICM (Tozzi & Norman 2001).

The fraction of the total cluster baryonic mass originating as Pop III HN progenitors is

$$\frac{M_{\rm HNP}}{M_{\rm ICM} + M_{\rm stars}} = 0.019 \left(\frac{f_{\rm HN}}{0.005}\right) \left(\frac{\eta_{\rm II}}{0.019{\rm M}_\odot{}^{-1}}\right) \left(\frac{M_{\rm prog}}{200{\rm M}_\odot}\right) \frac{\mu}{1+\mu}, \tag{1}$$

where $M_{\rm prog}$ is the mean HN progenitor mass, and μ is the cluster ratio of stars-to-gas as

previously defined. That is, the mass density of Pop III stars in units of the critical density,

$$\Omega_{\rm III} = 7.1\ 10^{-5} \left(\frac{\Omega_{\rm baryon}}{0.041}\right) c^{-1} {b_1}^{-1} {b_2}^{-1}, \tag{2}$$

for $f_{\rm HN} = 0.005$, $\eta_{\rm II} = 0.019\ {\rm M}_\odot{}^{-1}$, $M_{\rm prog} = 200{\rm M}_\odot$, and $\mu = 0.1$. $\Omega_{\rm baryon}$ is normalized to the BBN value, c (< 1) is the fraction of Pop III stars that produce HN and b_1 and b_2 are cluster "bias" factors encompassing any over- or under-concentration of baryons and any relative Pop III stellar formation probability enhancement in clusters relative to the universal average, respectively. Ostriker & Gnedin (1996) estimated $\Omega_{\rm III}$ from self-consistent, semi-analytic modeling of the evolution of the Jeans mass through the epoch of IGM reheating. Their results imply $b_2 \approx 17$ (for $c \sim 1$, $b_1 \sim 1$). A value $b_2 >> 1$ is not unexpected: Pop III stars are unlikely to have formed as readily (or, perhaps, as early or with the same IMF) outside of these regions of highest primordial overdensity. A low value of $\Omega_{\rm baryon}$ (as, e.g., implied by a high primoridal deuterium abundance) would indicate $b_1 > 1$ and a correspondingly lower value of b_2.

4. Discussion and Predictions

4.1. Summary of Hypernovae ICM Enrichment

If the stars responsible for enriching the ICM and the stars observed today in cluster early-type galaxies originate in the same early star formation epoch, then the amount of Si observed in clusters cannot be explained with standard SNII yields and the solar neighborhood IMF: the number of SNII per stellar mass must be increased by nearly a factor of two through invocation of a flat or bimodal IMF. However, recent observations of the ICM ratio of O/Si that are well below solar cast doubt on this explanation. For reasonable SNIa/SNII ratios, Si and O are predominantly synthesized in SNII that produce a roughly solar O/Si ratio.

Although HN nucleosynthesis calculations are at an early stage, depleted O abundances caused by more extensive O-burning are likely to persist. Thus, it is worth studying their possible role in ICM enrichment – particularly in light of their potential to preheat the ICM and their possible connection to the elusive Population III stars. I investigate two classes of HN contributions. Firstly, I consider the case where some fraction (perhaps the most metal-poor) of SNII progenitors from a unimodal IMF give rise to hypernovae with increased explosion energy and nonstandard yields, as in the calculations of Nakamura et al. (2001). Their contribution can indeed lower the O/Si ratio to the observed level, but only if there are approximately equal numbers of HN and conventional SNII. Moreover, this implies

an energy production of > 20 keV per ICM particle – sufficient to unbind the ICM of even the most massive clusters unless most of the $\sim 10^{64}$ erg of energy is radiated – as well as negligible enrichment by SNIa.

ICM abundances are more naturally explained with a substantial contribution from Population III hypernovae originating in an earlier, independent star formation mode. An absence of metals reduces cooling and leads to a very large Jeans mass: Pop III stars are likely to form with an extremely top-heavy IMF (Larson 2001). (A hybrid scenario is also possible if the Pop III IMF is itself bimodal; Nakamura & Umemura 2001.) Very massive, metal-free stars naturally give rise to hypernovae with enhanced yields and skewed abundance ratios compared to ordinary SNII. Utilizing a pair of representative cases from Heger et al. (2001), I find that if one such HN contributes to ICM enrichment for every 200 SNII, the observed *proportions* of Fe, Si, and O are simultaneously explained. Also, the additional contribution from ordinary SNII required to explain the *amount* of these elements is consistent with the LIMF, in keeping with evidence for a universal IMF (Wyse 1997); this is not true of an alternative scenario for simultaneously explaining the relative amounts of O, Si, and Fe by reducing SNII O yields. Finally, the associated preheating of ~ 0.1 keV per particle is sufficient to account for the observed cluster "entropy floor" (e.g., Lloyd-Davies, Ponman, & Cannon 2000), since it is deposited at $z \gtrsim 10$ when the more diffuse ICM was especially susceptible to a shift to a high adiabat (Tozzi & Norman 2001).

Under this scenario, cluster O primarily (90%) originates from SNII, while comparable contributions from SNII and HN account for Si. About one-third of the ICM Fe originates from SNII, with HN contributing some amount $\leq$ one-half (this is uncertain due to the steep dependence of HN Fe yields on progenitor core mass) and SNIa the rest. The partial decoupling of the origins of these elements has implications for expectations of future accurate X-ray measurements of ICM abundances, in addition to the prediction that subsolar O/Si ratios will be confirmed and found to be common. Correlations of the mass in each of these metals versus optical light may have offset zero-points relative to the case where all metals share a monolithic origin. Cluster-to-cluster variations in metal mass-to-optical-light ratio may display an elemental dependence with, e.g., M_{Si}/L displaying a greater scatter than M_O/L. Si abundances are predicted to be substantial even at very high redshift, and evolve more slowly than O abundances.

4.2. Implications for the Enrichment of the IGM

In current models for the chemical evolution of the IGM, the enrichment is dominated by supernovae associated with early-epoch, Population II star formation. Yields of $\sim 2-5\times$

the solar mass fraction of metals for each solar mass of star formation are typically required to match the C abundances measured in Lyα forest clouds (Gnedin 1998; Cen & Ostriker 1999; Aguirre et al. 2001; Cen & Bryan 2001). Population III stars have been proposed as providing the radiation that reionizes the universe (Ostriker & Gnedin 1996; Tumlinson & Shull 2000), while simultaneously pre-enriching the IGM to modest levels $\leq 10^{-3}$ solar (Ostriker & Gnedin 1996; Wasserburg & Qian 2000). However, if hypernova are produced by Population III as suggested here in order to explain ICM abundances, the implied pre-enrichment may be significantly enhanced. For the value of $\Omega_{\rm III}$ calculated by Ostriker & Gnedin (1996) (corresponding to a Pop III stellar mass per baryon ratio 17 times less than proposed here for the ICM) the Heger et al. (2001) HN yields imply IGM pre-enrichment to as much as $\sim 2.5\ 10^{-3}$ solar metallicity with very non-solar abundance ratios. While O (and elements of lesser atomic weight) are synthesized in amounts small compared to those observed in Lyα forest clouds, Si attains $> 10^{-2}$ solar abundance at $z \sim 10$. Since subsequent Pop II enrichment must then be invoked to produce $\sim 10^{-2}$ solar C abundances, a Si/C ratio about twice solar is expected. This is consistent with measured UV line ratios (Giroux & Shull 1997; Songaila 1998) in the clouds. Thus a contribution to IGM enrichment from Pop III hypernovae can alleviate the requirement of excessive Population II yields, while explaining a likely observed overabundance of Si. Similar overabundances of, e.g., S and Ca – but not N or O – relative to C are predicted – the former being produced in roughly equal amounts by Populations II and III, the latter primarily by Population II.

5. Concluding Remarks

Signatures of hypernova explosions of very massive Population III stars are found in the numbers and abundance pattern of low-metallicity Milky Way stars (Ferrara & Hernandez 2001; Umeda & Nomoto 2001) and in the population of $> 100\ M_\odot$ black holes (Madau & Rees 2001). I have demonstrated that these extreme primordial events also leave a thermal and chemical imprint on the IGM and ICM. Direct observation of hypernova explosions and/or their progenitors with the *Next Generation Space Telescope*, in concert with advances in calculations of HN yields, could provide direct confirmation of the important role of Pop III in enriching both the IGM and ICM. Population III hypernovae may constitute an important feedback mechanism during the earliest galaxy formation era and ought to be be considered in semi-analytic galaxy formation calculations.

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Table 1. SN Yields and HN Enhancement Factors

	$f_\odot$	$y_{\rm Ia}$	$\langle y_{\rm II} \rangle$	$\epsilon_{\rm HN}$	$\epsilon_{\rm HN3}(100)$	$\epsilon_{\rm HN3}(120)$
0	$9.6\ 10^{-3}$	0.15	1.7	0.68	25	20
Si	$7.1\ 10^{-4}$	0.16	0.14	1.9	160	180
Fe	$1.3\ 10^{-3}$	0.74	0.10	3.5	50	270

Note. — Yields are in $M_\odot$.

Table 2. Results for Various Supernova Combinations

$f_{\rm Ia}$(Fe)	$\rm f_{HN}$	Ia/II	O/Fe	Si/Fe	$\eta_{\rm II}$[a]	$kT_{\rm SN}$[a]	Fe[b]	$kT_{\rm SN}$[b]
0	0	0	2.2	2.5	0.056	1.2	0.14	0.40
0.25	0	0.045	1.7	2.0	0.042	0.93	0.18	0.42
0.38	**0**	**0.083**	**1.4**	**1.7**	**0.035**	**0.80**	0.22	0.44
0.5	0	0.135	1.1	1.4	0.028	0.67	0.27	0.46
0.66	**0**	**0.26**	**0.78**	**1.1**	**0.019**	**0.51**	**0.4**	**0.51**
0.75	0	0.405	0.58	0.91	0.014	0.42	0.54	0.57
0	**0.5**[c]	**0**	**0.83**	**1.6**	**0.025**	**26**	0.31	20
0.23	**0.5**[c]	**0.092**	**0.65**	**1.3**	**0.019**	**20**	**0.4**	**20**
0.59	**0.005**[d]	**0.24**	**0.84**	**1.7**	**0.018**	**0.56**	**0.41**	**0.58**
0.20	**0.005**[e]	**0.079**	**0.84**	**1.7**	**0.019**	**0.58**	**0.4**	**0.57**

Note. — Fe abundances and abundance ratios are relative to solar, $kT_{\rm SN}$ is in keV, $\eta_{\rm II}$ in $\rm M_{\odot}{}^{-1}$.

[a]values corresponding to solar Fe abundance

[b]values corresponding to Local IMF value of $\eta_{\rm II}$

[c]hypernovae as in Nakamura et al. (2001)

[d]hypernovae as in Heger et al. (2001), $M_{\rm core} = 100$

[e]hypernovae as in Heger et al. (2001), $M_{\rm core} = 120$

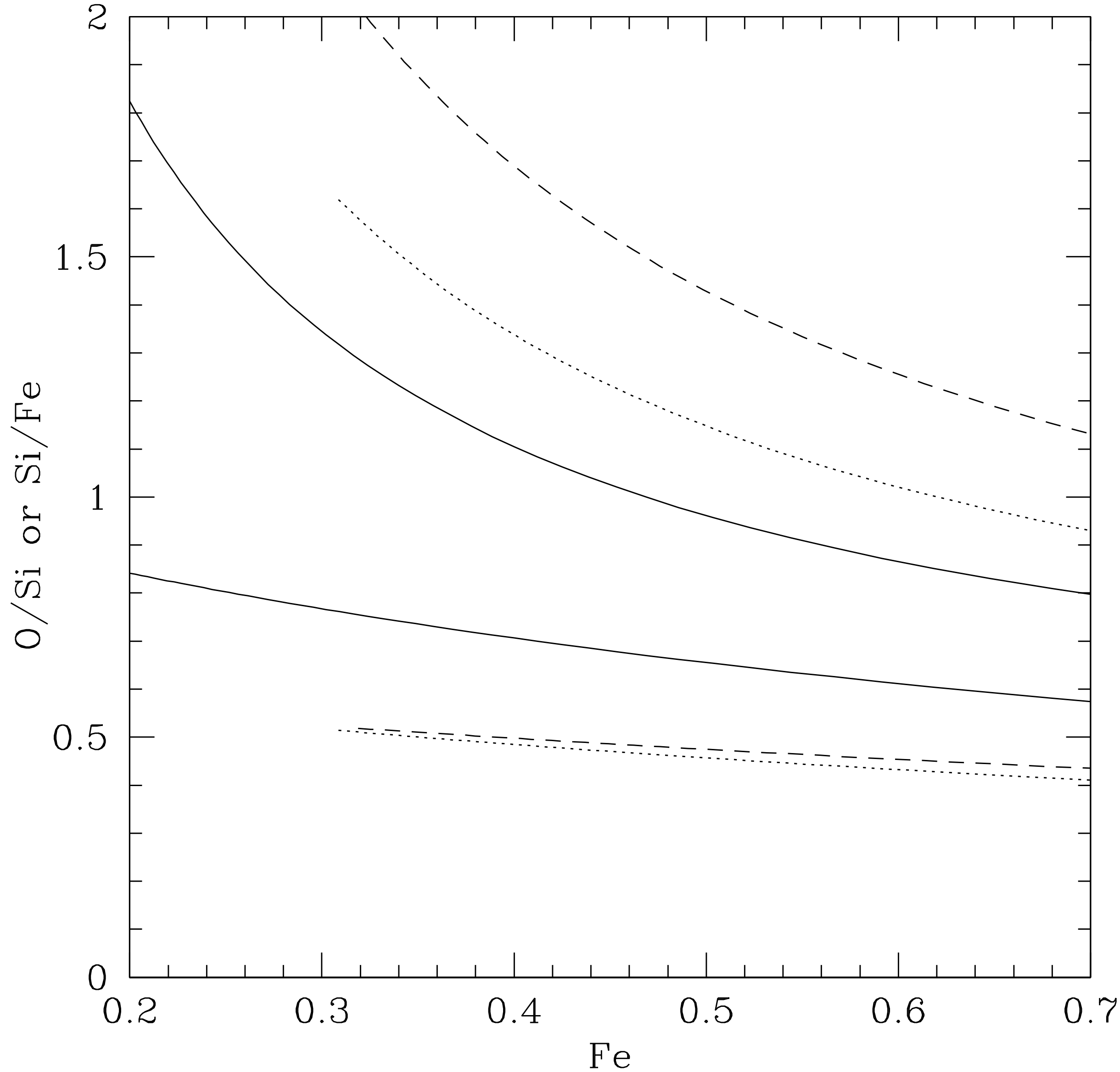

Fig. 1.— O/Si (lower curves) and Si/Fe (upper curves) abundance ratios as a function of Fe abundance for the LIMF specific SNII rate. Solid curves illustrate the case of no hypernovae, dotted curves hypernovae as in Nakamura et al. (2001), dashed curves hypernovae as in Heger et al. (2001).